FERMILAB-Proposal-0644

The University of Michigan

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May 7, 1982

Leon Lederman, Director
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510

Dear Leon:

We are submitting the enclosed revision for P644 which essentially replaces the entire P-644 proposal.

Sincerely,

Byron Roe
for the P644 collaboration

BR:sm

31 pgs.

P644

Proposal Update April 1982

Preface

This update is meant to replace the original P644 proposal.

We request that we run in the Neutrino area with a high Z (Pb) detector that we will evolve from our present E613/P716 prompt neutrino detector now operating in the Meson Area. We are no longer considering a detector built up of plates made of concrete or other low-Z material.

Summary

We request that we run a prompt neutrino experiment in the Tevatron Neutrino Area prompt beam. Our detector would be located about 75 meters from the target. We ask for a run of 10^{18} protons on target. Our detector will have:

High event rate

Large solid angle

Good neutral current - electron neutrino separation

Good energy resolution

Our P644 detector will evolve from our present E613 detector. We will indicate some of the modifications being considered later. The present E613 detector, shown schematically in Fig. 1, consists of a 150 metric ton calorimeter made up of 30 modules. Each module contains 12 teflon-coated lead plates 6.3 mm thick, to give a total of 14.4 radiation lengths, 0.5 hadron absorption length, and 105 gm/cm^2 per module. Light from the liquid scintillator surrounding the plates is detected by 10 photomultiplier tubes per module. Each module is followed by two PWC planes, one with horizontal and one with vertical wires on 2.54 cm centers. (See inset to Figure 1.) These are operated in a proportional mode with analog pulse height readouts. The 6000 PWC wires have a wire-to-wire gain uniformity of 10% without software corrections and the readout is linear for showers with as many as 100 particles per wire. The calorimeter is followed by a muon spectrometer with drift chambers and solid iron magnets.

The transverse dimensions of the sensitive region are 3 m wide by 1.5 m high. Beam center is 0.75 meters from one side horizontally and centered vertically. The horizontal asymmetry allows us to record neutrino interactions out to a 40 mr production angle.

A set of six calorimeter modules was calibrated in a test beam to determine the energy scale. The calorimeter energy response was found to be quite linear and to have a resolution

$$\sigma/E = .55/\sqrt{E}\ (\text{GeV}) \text{ for hadrons and}$$
$$.27/\sqrt{E}\ (\text{GeV}) \text{ for electrons}$$

Ability to Separate Charged-Current Electron Events from Neutral Current Events

With our present 400 GeV run we have been able to separate out a sample of charged-current electron neutrino events which is about 83% pure and contains about 81% of all the charged-current electron neutrino events. (See Figure 2.)

We do this by looking at the ratio of energy in the first module or two to the energy in the rest of the modules. Because of our large ratio of interaction length to radiation length (~.5/14) in a module, most of the energy from electrons, photons, and π° appears in the early modules, while much of the hadronic energy appears later.

The specific algorithm used presently goes in two steps. First, we use the ratio of energies in the first two modules to estimate the position of the vertex in module 1. This information is then used to form an estimate of the energy deposition in the first 100 g/cm^2 of detector immediately downstream of the ν interaction. This energy is labeled E_1. Second, we form the variable $Y_0 = 2*(E_{total}-E_1)/E_{total}$ where $E_{total}-E_1$ is the energy in modules excluding the first "shifted" module. Most electron neutrino charged current events are expected to have low values for Y_0, whereas neutral current events have Y_0 values peaked at unity.

In Figure 2 the plot labelled NC consists of simulated neutral current events obtained by taking real muon neutrino charged current events and removing the muon. (We can discriminate against cosmic ray background because we records events from one second of beam off for every one second of beam spill.)

Comparison of Neutrino Detectors for Prompt Neutrinos

Detector	Distance from target (m)	Mass (tons)	Fiducial mass (tons)	Effective maximum angle (mr)	Rel. No. events at 900 GeV > 15 GeV	Separate ν_{ecc} from nc	$\frac{\Delta E}{E}$ (percent)
P644 (existing E613)	75	150	80	30	1	Yes	$55/\sqrt{E}$
Lab E	107	1100	680	9.3	4.9	No	$100/\sqrt{E}$
15' B.C.	160	--	~20	7	0.13	Yes	--*
Lab C	235	350	150	6.1	0.38	Yes	$35/\sqrt{E}$ E < 100 $105/\sqrt{E}$ E > 200

*$E_{resolution}$ poor for electron neutrino events

We note that our detector is designed to look at a large range of production angles. The Neutrino Area Tevatron beam is designed to be run at several production angles; 0, 20, 40 mr, etc. We cover 0-30 mr in one exposure and would get more neutrinos per proton at high angles than the lab C detector, for example, will obtain in a dedicated high angle run.

In a Neutrino Lab run centered at high angles we can choose either to get full intensity by having the 0° beam strike our apparatus, or to look at very high angles. Thus, if the beam is set for 20 mr our detector can see events out to 50 mr.

Event Rates

We use for reference the central production model of J. Leveille[1]. In this model $\sigma \propto (1-x)^5 e^{-3.45m_\perp}$, where $m_\perp = p_\perp^2 + m_D^2$. Figure 3 shows the predicted dependence on proton energy and the calculated relative acceptance as a function of proton energy. We note that the model predicts a smaller cross section than that observed at the ISR[2]. (See Figure 4.) Furthermore, if there is a large diffractive component as suggested by the ISR results the average energy will be higher than calculated here.

We obtain, for 10^{18} protons on a W target,

E_{GeV}	Number Prompt ν Events	Q^2 $(GeV/c)^2$	Number $\nu_\mu cc$ Events
> 15	225,000	> 10	35,000
>100	75,000	> 25	14,000
>200	16,000	> 50	4,000
>300	1,100	>100	500

We would also expect >1,000 neutrinos from B decay. These would have a much broader $p_\perp$ distribution than we have now and should be distinguishable. (See

Figure 5.)

Signal to Noise for Highest Density Target

The ratio of prompt to non-prompt events for their full density target has been measured by various groups.

E613 (our present experiment) finds for 400 GeV running on W a prompt/non-prompt ratio of 1.1 for ν_μ cc and 4.2 for 0μ events. CCFRS finds (for 350 GeV running looking for prompt muons from a 3/4 density Fe target) a prompt/non-prompt ratio of 0.1. Their background is increased by a large number of low mass dimuon events and also by the fact that in $\pi \to \mu\nu$ decay the muon tends to be high energy and the neutrino low energy in the lab.

The CDHS group at CERN finds, for 400 GeV running with a Cu target, $\nu_\mu$cc prompt/nonprompt = 0.4 Their background is increased because Cu is less favorable than W and because the neutrinos from π decay are largely concentrated in the forward direction. (Their experiment subtends ~2 mr.)

At higher energies the fraction of the cross section involving charm production is expected to increase. Furthermore, at higher energies the fraction of π and K mesons which decay will decrease. The signal to noise (on W) thus should go up by a factor of about 3 to 5 relative to that at 400 GeV.

In the Neutrino Lab the muon shielding will decrease the muons at our detector by a large factor relative to our Spring '81 run. Even with a short spill of 1-2 ms, 10^2-10^3 μ/spill should not be a problem. Beam center will be about 2' higher off the floor than now. This should help reduce the triggers due to floor showers. (These are our principal trigger background in our 400 GeV running.) Cosmic rays will be reduced to a very low level by the

[1]J. Leveille, private communication.

[2]F. Muller, Hadroproduction of Charmed Particles, p. 141, Proceedings of the IV Warsaw Symposium on Elementary Particle Physics (1981).

short spill, but we have demonstrated at 400 GeV that we can remove cosmic ray triggers efficiently offline. We should be able to handle either a long or a short spill.

Modifications Being Considered for the Apparatus from the E613 Configuration

1. We will need buffered readouts for the PWC and drift chambers if we are to run with a 1-2 ms spill and record more than one event per spill.
2. We will ask the lab to add one more toroid for muon momentum determination in the higher energy Tevatron beams.
3. We are considering several options for improving the calorimeter itself such as rebuilding the lead-scintillator tank to increase the segmentation and/or replacing the liquid scintillator with plastic scintillator.
4. We are considering interspersing drift chambers in the calorimeter. About 7 drift chamber planes with 0.5-1 mm resolution allow a good measurement of Q^2 for $Q^2>10$ $(GeV/c)^2$ from the muon angle:

E_ν (GeV)	100	500
Q^2 $(GeV/c)^2/\theta_\mu$ (mr)	θ_μ (mr)	
100	>100	>20
10	> 32	> 6.4
1	> 10	> 2

Multiple scattering in the lead gives for y=1.2 a contribution,

E_ν (GeV)	100	500
	θ_μ (mr)	
4 modules	3	0.3
8 modules	4.2	.42

A two point measurement of the muon angle 4 modules apart with 0.5 mm resolution per measurement gives a 0.7 mr error in the muon angle.

We conclude that for $Q^2 > 10\ (\mathrm{GeV}/c)^2$ we should be capable of good resolution in Q^2.

Work on the Neutrino Area Prompt Beam

We are working with the Neutrino Area people in understanding muon backgrounds in a prompt beam. Our beam dump muon fluxes provide a benchmark for testing Neutrino Area Monte Carlo programs. In the Spring 1981 run we had about 8 times the number of muons predicted by M. Peter's Monte Carlo program as it then existed. However, the program did succeed in predicting the relative rates in different places and with different amounts of shielding.

Our group has experience with monitoring the incoming proton beam for upstream background sources. We believe our expertise in this area can be of considerable use in setting up the monitoring system for the Neutrino Area.

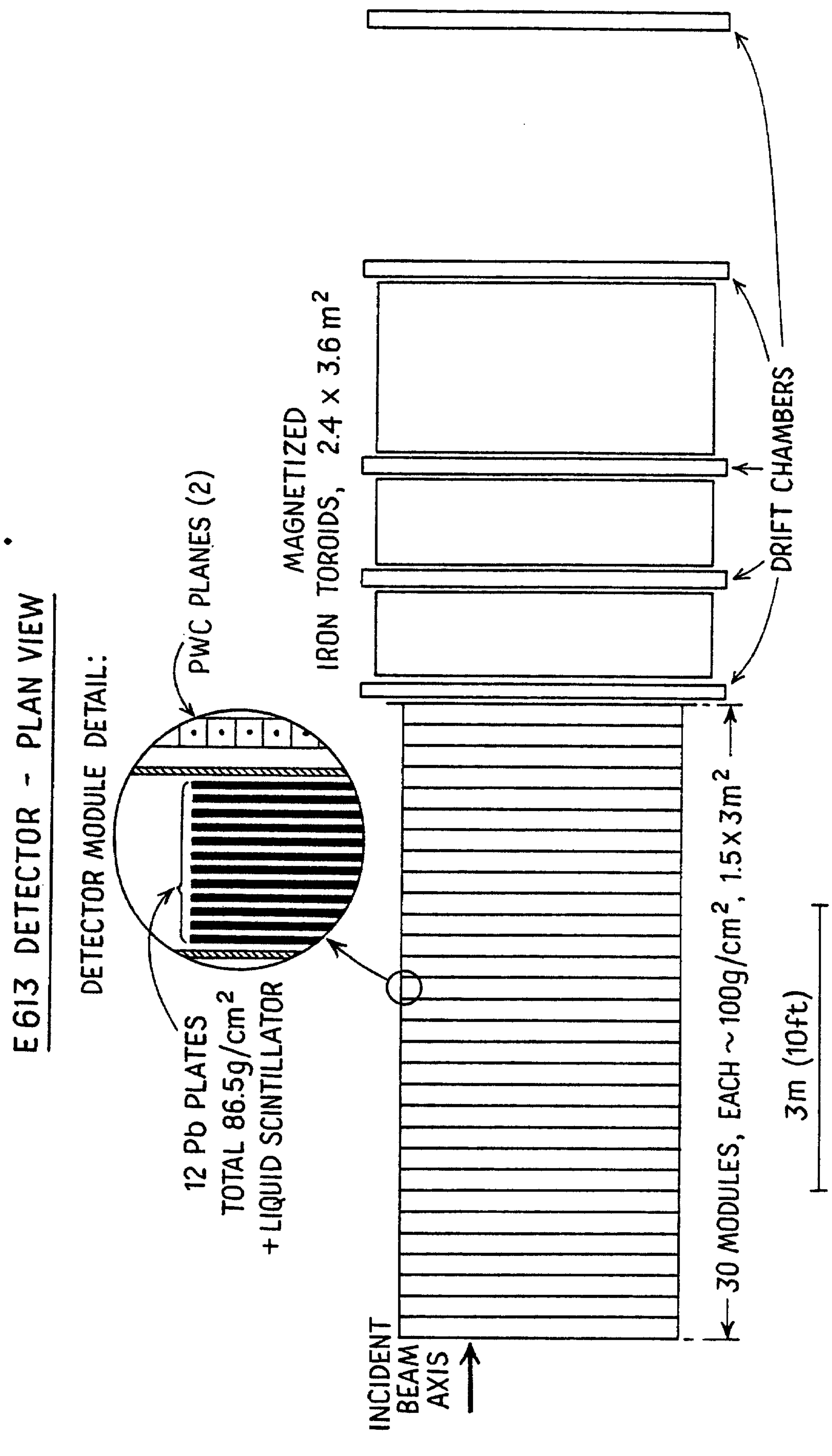

E 613 DETECTOR - PLAN VIEW
DETECTOR MODULE DETAIL:
PWC PLANES (2)
12 Pb PLATES
TOTAL 86.5g/cm²
+LIQUID SCINTILLATOR
MAGNETIZED
IRON TOROIDS, 2.4 x 3.6 m²
DRIFT CHAMBERS
INCIDENT
BEAM
AXIS
30 MODULES, EACH ~100g/cm², 1.5 x 3m²
3m (10ft)

Figure 1

Above cut: $\underline{83\%}$ $\nu_e \bar{\nu}_e$ CC
11% NC
6% Cosmic

This cut selects $\underline{81\%}$ of all ν_e CC events

ETOT vs y_0 for W

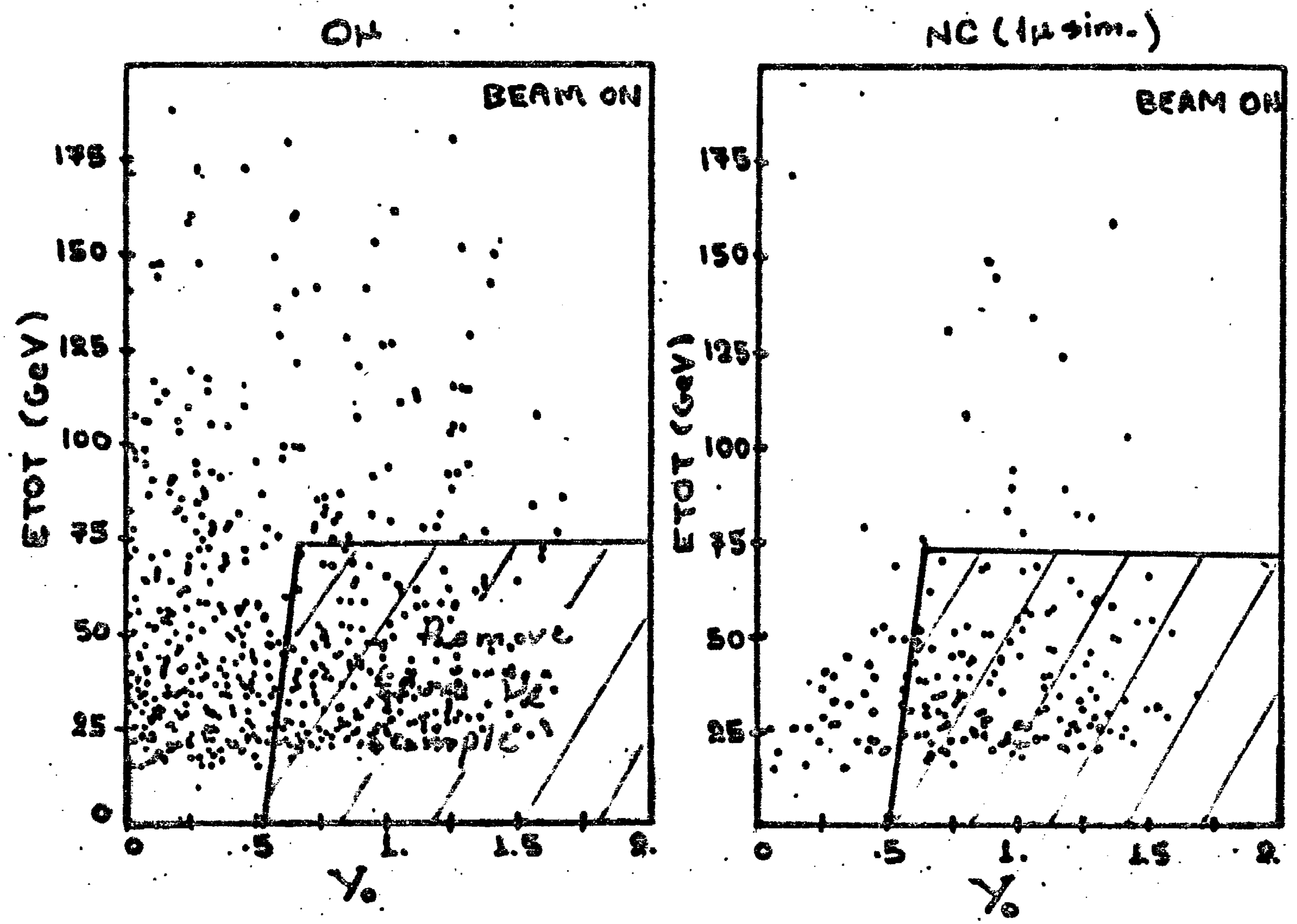


Figure 2

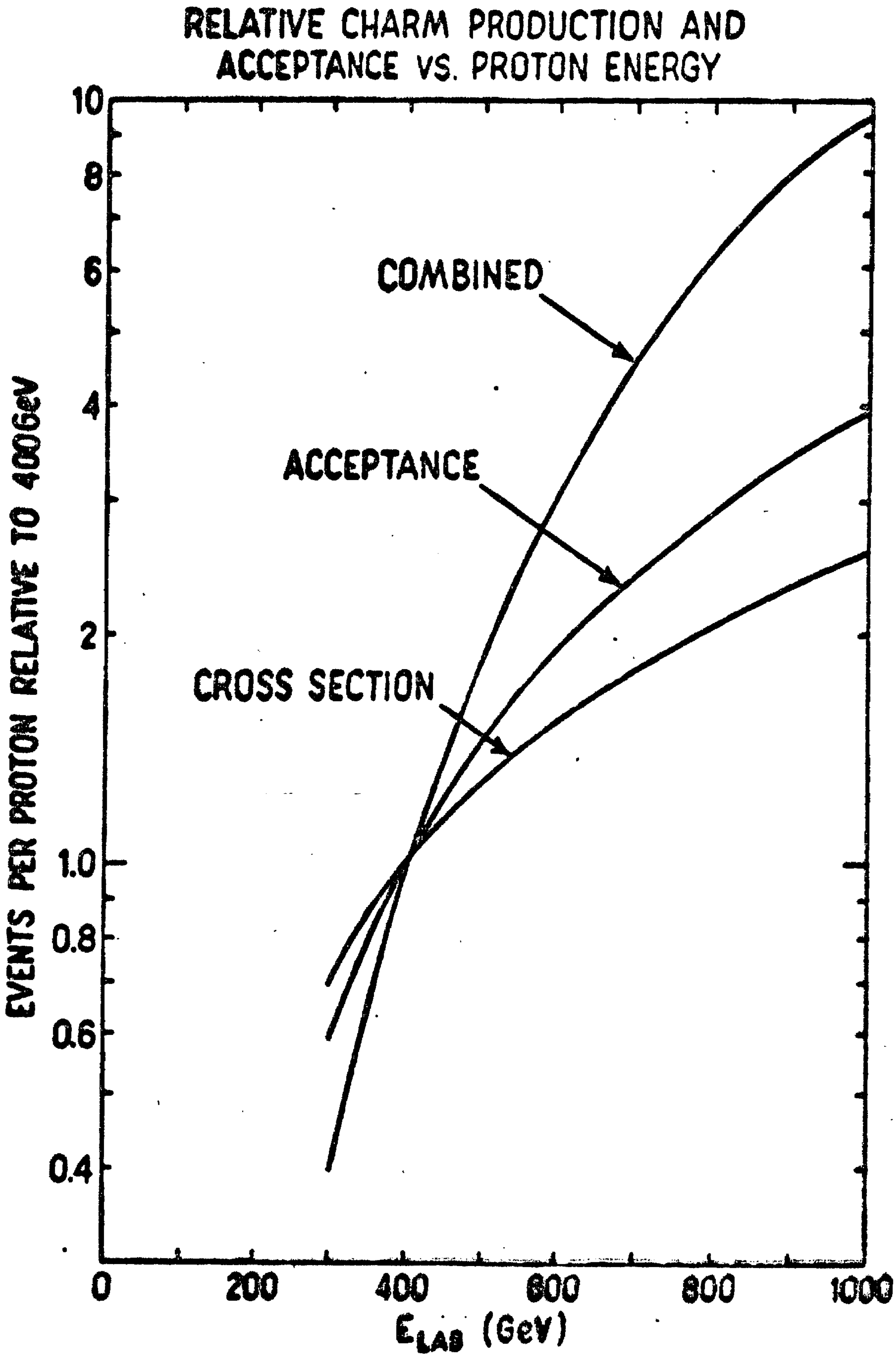
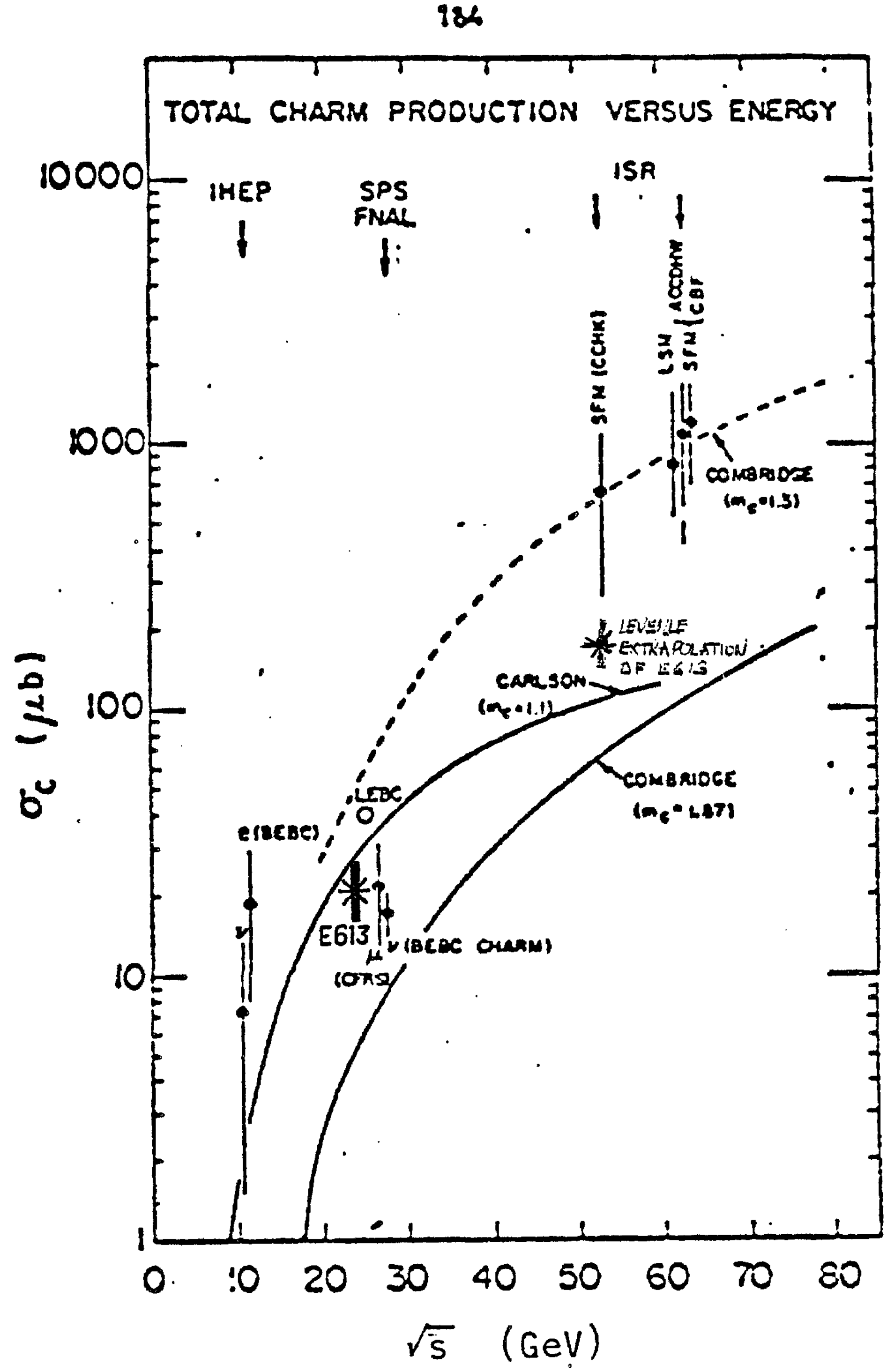

RELATIVE CHARM PRODUCTION AND ACCEPTANCE VS. PROTON ENERGY
COMBINED
ACCEPTANCE
CROSS SECTION
EVENTS PER PROTON RELATIVE TO 400GeV
10
8
6
4
2
1.0
0.8
0.6
0.4
0
200
400
600
800
1000
E_{LAB} (GeV)

Figure 3



From F. Muller, Hadroproduction of Charmed Particles, p.141, Proceedings of the IV Warsaw Symposium on Elementary Particle Physics (1981)

Figure 4

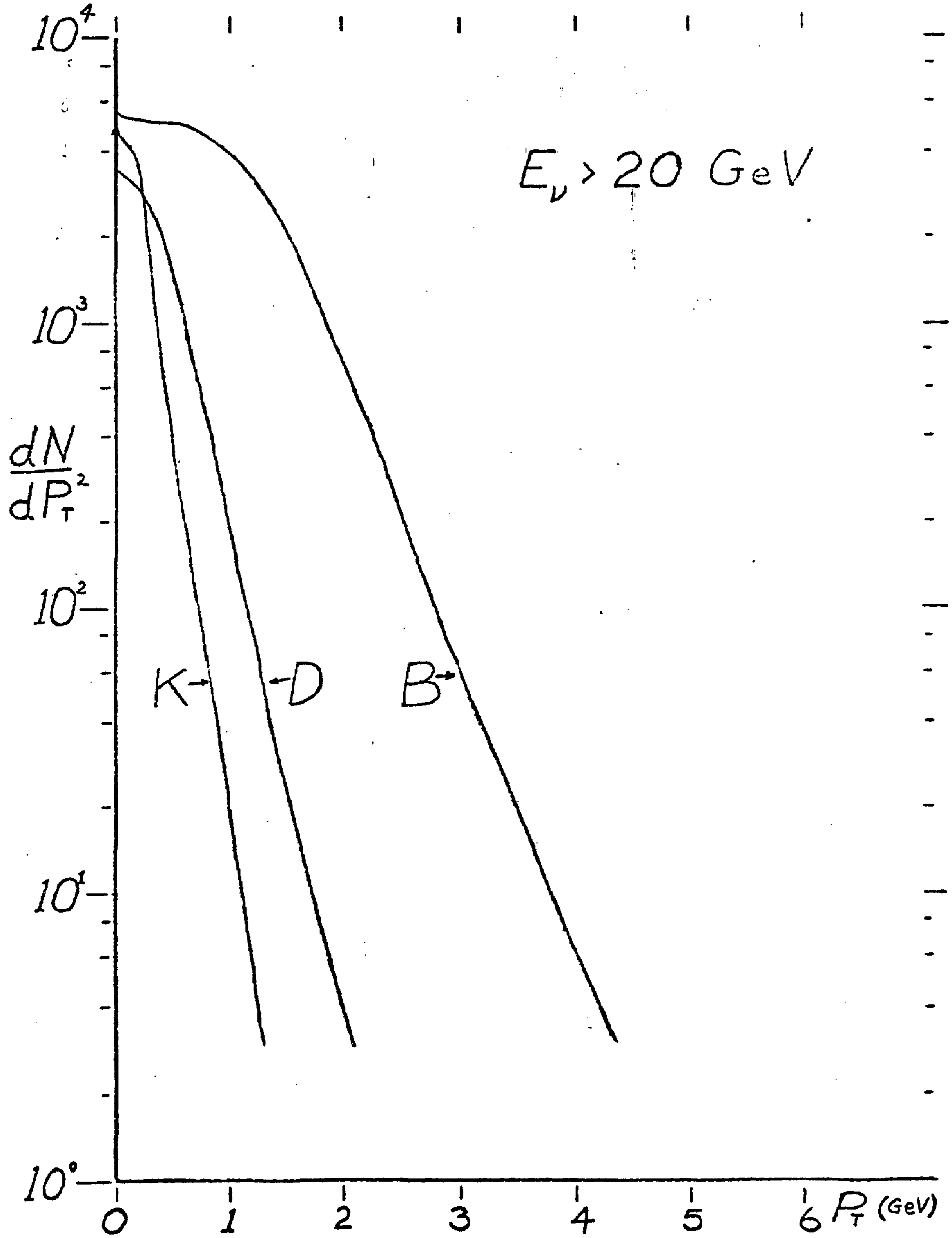


Figure 5

FERMILAB-Proposal-0644

Further Studies of Prompt Neutrinos with the E-613 Detector

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SUMMARY

We propose to improve and enlarge the E-613 detector to make a finer grained detector more suitable for τ-neutrino physics and for studying neutrino oscillations. Details of the design of the detector will depend on our experience in E-613, further Monte Carlo studies, and possibly tests of a prototype with beam. At present we contemplate a detector which would have twice the mass of the present one with proportional readout of approx. 20,000 wires compared to $\approx$ 6500 at present. With the increased detector mass and a factor of five increase in average intensity we expect $\sim 2 \times 10^5$ prompt neutrino events and $\sim 2 \times 10^3$ $\nu_\tau \to \tau$ events with subsequent decay of the $\tau^\pm$ to $\mu^\pm + \nu_\tau + \nu_\mu$. Running could be at energies from 200 to 1000 GeV.

THE PRESENT DETECTOR

The E-613 detector, shown in Fig. 1, consists of 30 lead-scintillator calorimeter modules, each 5 ft. high by 10 ft. wide with a mass of 5 metric tons. Each module is viewed by 10 photomultiplier tubes. After each module are two planes of proportional wire chambers with pulse height readout. One plane of each pair of PWC's has wires horizontal; the other has wires vertical. The wires are on 1" centers. By fitting energy deposition profiles we can effectively interpolate between wires and obtain a resolution for tracking the energy deposition which is considerably better than the wire spacing. The calorimeter is followed by a muon spectrometer made up of solid iron toroids with drift chambers to track the muons.

The calorimeter is shielded by a 2' thick heavy concrete roof upon which cosmic ray veto counters are located.

The present beam dump is shown in Fig. 2. A notable feature is the pitching magnet just ahead of the target. This magnet aims the proton beam upward so that at the detector the prompt neutrino flux is centered about 12" above the nominal Meson Lab beam height. Thus neutrino events from background sources upstream of the pitching magnet will be distinguishable from neutrinos produced in the target by their spatial distribution alone. This feature of the experiment will provide a crucial test of the origin of our events which is especially important in searching for possible neutrino oscillations.

PROPOSED MODIFICATIONS

We propose to enlarge the present detector to approx. twice the present mass. The added elements will be of low Z material and have much finer grained sampling of the energy deposition. This will greatly improve the resolution in missing $P_\perp$ which is vital in distinguishing tau neutrinos from ordinary neutrinos.[1,2]

The most economical and convenient choice of a low Z material for the detector seems to be ordinary concrete (appropriately reinforced with steel or aluminum). A possible configuration for the enlarged detector is shown in Fig. 3. Each of the 15 cells would consist of two of the lead-scintillator modules from the present detector preceeded by 8 slabs of concrete; each slab will be 4" thick and a single PWC plane would follow each concrete slab. The PWC planes would be alternately x and y with a total of 180 planes, three times as many as in the present array.

One advantage of interspersing new detector elements with the present lead-scintillator modules is that no new triggering elements would be required.

ν_τ SEARCH

Our rate estimates are based on an assumed proton flux of 5×10^{12}/pulse on a hevimet target with prompt ν production cross sections from the CERN beam dump experiments.[3] We assume an A^1 production cross section to extrapolate from the copper target used at CERN to tungsten (hevimet). Cross sections for ν_τ production and $\tau\to\mu+\nu_\mu+\nu_\tau$ branching ratios are taken from C. Albright et al.[2]

With 5×10^{12} protons incident at 400 GeV we estimate $\sim$ 0.5 prompt ν events with $E_{vis} > 10$ GeV per spill. At 5000 spills per day and 100 days of running, this is 2.5×10^5 total prompt ν events. Albright et al.[2] estimate that the $(\nu_\tau+\bar{\nu}_\tau)$event rate with the τ subsequently decaying into a μ is $\sim$ 1% of the prompt ν rate, so this corresponds to $\sim$2500 useful ν_τ events. Even after the cuts prescribed by Schrock et al. to isolate the ν_τ events, we can expect several hundred events.

Comparable rates could be expected with a 1000 GeV beam. The increased ν fluxes would roughly compensate the lower repetition rate.[4]

An important advantage of our detector in searching for the tau neutrino is the large solid angle it subtends. At larger angles and higher E_ν the ratio of ν_τ to $(\nu_\mu+\nu_e)$ increases significantly [Table I]. This should serve as an important check that we are actually observing ν_τ's.

Our own Monte Carlo studies of the Albright-Schrock technique indicate that with the angular resolution for hadron showers anticipated for the CHARM and E-594 detectors the rejection of background from ν_μ events is only about 20:1. We are continuing to investigate various detector configurations to find the optimum choice. Possible further cuts on the data to enhance the ν_τ signal are also being studied. There is also the possibility that $\nu_e \to \nu_\tau$ oscillations might dramatically enhance the ν_τ signal.

NEUTRINO OSCILLATIONS

The three groups taking part in the beam dump experiment carried out at CERN in the spring of 1979 have all reported values for the ratio

$$R = \frac{\text{Number of prompt electron events}}{\text{Number of prompt muon events}}$$

which are substantially smaller than unity. The presently available determinations of R are the following

BEBC[3]	$R = 0.49 \pm 0.17$
CHARM[3]	$R = 0.59 \pm 0.22$
CDHS[5]	$R = 0.62 \pm 0.13$

from which the combined value $R = 0.574 \pm 0.096$ can be derived.

If the prompt neutrinos come from decays of charmed particles we would expect R=1. No convincing explanation for this discrepancy exists at present. The possibility that it may be due to oscillations of ν_e's into ν_τ's (or perhaps even other kinds of neutrinos so far unsuspected) has been suggested in Reference 6. This explanation requires mixing angles α of about 20° and values of $\delta m = \sqrt{|m_3^2 - m_1^2|} \gtrsim 7$ eV which are not excluded by any experimental observation available at present.

V. Barger et al.[7] have also reanalyzed the situation regarding possible neutrino oscillations. They do not consider the CERN beam dump results. They conclude that the reactor, deep mine, and accelerator data are consistent with ν oscillations with $\delta m \gtrsim 0.1$ eV. One of their "solutions" corresponds to a $\delta m \sim 3$ eV; however, they seem to favor the solutions with smaller δm which are not consistent with the CERN beam dump results.[6] In view of the uncertainty in the experimental situation, there seems to be no justification for eliminating the possibility of ν oscillations with $\delta m >> 1$ eV. [Cosmological arguments suggest that $m_{\nu_\tau} \lesssim 50$ eV. This limit is inferred from the density of the universe which is subject to large uncertainties.]

The subject of neutrino oscillations is currently in a state of such rapid evolution that these remarks should serve primarily as a reminder that neutrino oscillations are a topic of lively interest, and that any experiment which may significantly clarify this situation is of considerable importance.[9]

Maximum sensitivity to ν oscillations occurs when $E_\nu/L \sim (\delta m)^2$ where L is the distance between the neutrino source and detector and E_ν is the neutrino energy. Thus our detector with $L \approx 60$ m would be sensitive to larger δm than the CERN detectors.

If $\nu_e \to \nu_\tau$ transitions do occur, the ratio of electron neutrino to muon neutrino events will vary with E_ν in a characteristic way. The approximate expected behavior of $R \equiv$ (events with e)/(events with μ) is shown in Fig. 4 for $\sin^2 2\alpha = 0.4$, $\delta m = 17$ eV and $L = 60$ m.

Fortunately the M2 beam line is flexible enough to allow the proton beam to be targetted farther from our detector to vary L. If, for example, the proton beam is targetted on the steel collimator blocks on the Meson Lab target train and aimed at our apparatus, $L \cong 500$ m. Increasing the proton beam intensity will partially offset the decreased solid angle subtended by our detector. For $L = 500$ m the curve in Fig. 4 is appropriate for $\delta m \cong 5.9$ eV. It may also be possible to target at an intermediate location along the M2 line if it proves desirable to explore $60 < L < 500$ m.

If the effect observed in the CERN experiment is of spurious origin, it is most likely due to the decay of pions either produced by the scraping of the primary beam somewhere upstream of the target or leaking out of the dump target itself. In either case placing the detector as close to the target as possible is an advantage since the signal due to prompt neutrinos increases roughly as the square of the inverse of the distance between the target and the detector, while the background due to the pion decays is almost independent of the distance. The pitching magnet just ahead of our target provides a strong check on the origin of the events since neutrino events from the target will have a distribution centered over a foot above those from pion decays upstream.

OTHER PHYSICS

In E-613 we plan to make detailed studies of prompt ν production as a function of proton energy, atomic weight of the target, neutrino energy, and neutrino angle. We would, of course, wish to continue these studies up to 1000 GeV. At higher energies it may become possible to distinguish the contribution to prompt ν production from the decay of particles with naked beauty on the basis of the wider angular distribution these neutrinos would have. This argues for a close in detector capable of being moved to larger angles (i.e. - similar in concept to the E-613 detector).

There is also the distinct possibility that E-613 will uncover some new phenomena which we would want to follow up at higher energies. We can only speculate about such possibilities at present. In general, however, more massive particles are produced with broader angular distributions and decay with broader angular distributions. This is another strong argument for a detector which subtends a large solid angle.

We are also investigating the possibility of studying ν_e-e elastic scattering. The background from ν_e neutral current events poses serious problems, and it is not clear whether any practical electronic detector could provide sufficient rejection.

RUNNING CONDITIONS AND OTHER CONSIDERATIONS

Since this experiment is likely to be running when 1000 GeV external proton beams are beginning to be available, it is important to discuss how readily we can run at Tevatron energies. As previously noted, event rates will be roughly the same. It will take more magnetized iron in the beam dump to deflect the higher energy muons. This can be easily provided by adding another beam dump magnet to the present train, thus moving the target a few meters upstream. Some restacking and augmentation of the iron and concrete shield would also be necessary. We emphasize, however, that much of the physics, the ν_τ search and neutrino oscillations in particular, can be pursued with 400 GeV beam.

T.E. Toohig[8] has discussed the question of targetting 10^{13} protons/minute at 1 TeV onto a beam dump in the Meson Detector Bldg. He also discusses operation with 10^{13} protons/pulse at 400 GeV. He concludes that it is reasonable to target up to 10^{13} protons/pulse in the building if the muons are deflected vertically and personnel are kept out of areas like the catwalk downstream of the dump. Thus we anticipate no serious problems in increasing the intensity from the 10^{12} protons/pulse envisioned for E-613 to 5×10^{12} protons/pulse.

We propose that the costs of augmenting the detectors be borne by the experimenters and costs of enlarging the wonder building, modifying the beam dump, and rigging be borne by the laboratory.

We believe that upgrading the M2 beam dump to 1000 GeV and improving the E-613 detector is by far the most cost effective approach to future beam dump experiments at Fermilab. However, our group would not reject the possibility of relocating the E-613 detector in the Neutrino Laboratory We emphasize that any "new physics" is likely to be most conspicuous at relatively large angles and $P_{\perp}$. Thus any new neutrino facility should not preclude a study of large angle phenomena.

REFERENCES

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3. H. Wachsmuth, Proc. of the Int'l. Symposium on Lepton and Photon Interactions at High Energies, Fermilab, August, 1979.
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5. CDHS collaboration. Private communication.
6. A. De Rújula, M. Lusignoli, L. Maiani, S. Petcov, and R. Petronzio, TH.2788-CERN, Nov. 1979.
7. V. Barger, K. Whisnant, D. Cline, and R. Phillips, Univ. of Wisconsin Rep't. COO-881-135, Feb. 1980.
8. T.E. Toohig, Fermilab Tech. Memo TM-815, 2833.000, Sept. 22, 1978.
9. A recent preprint by F. Reines et al. indicates positive evidence for ν oscillations from reactor data which correspond to a $\delta m \gtrsim 0.6$ eV. Rumors of new results from the ITEP group measuring the spectrum from H^3 beta decay suggest a ν_e mass ~ 17 eV.

TABLE I - ν_τ and $(\nu_\mu+\nu_e)$ Fluxes, 1000 GeV

[From S. Mori, TM-848]

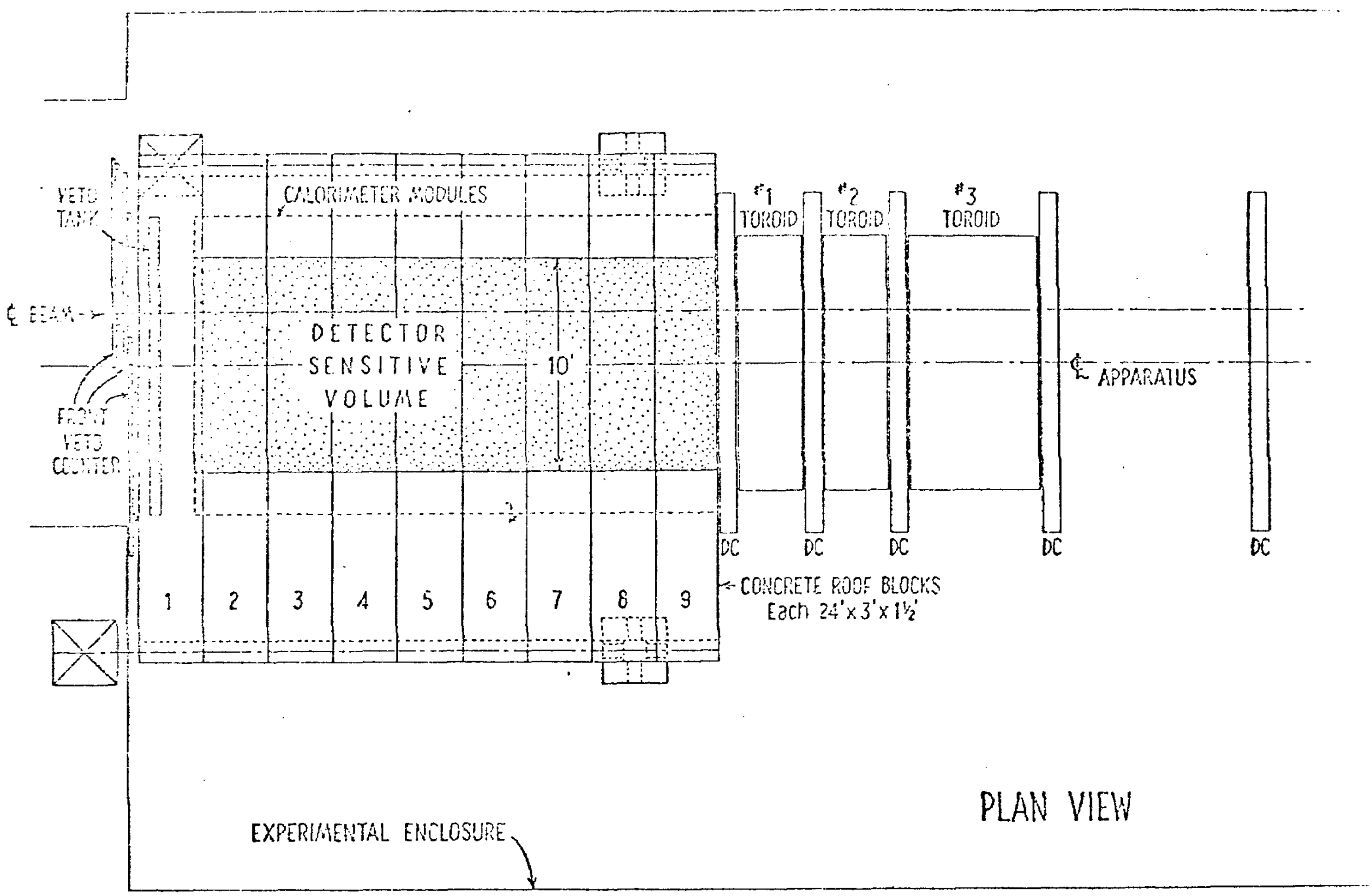
E_ν (GeV)	0-2 mr		4-6 mr		8-10 mr	
	$\nu_\tau+\bar{\nu}_\tau$ Flux*	$\frac{\nu_\mu+\nu_e}{\nu_\tau}$ †	$\nu_\tau+\bar{\nu}_\tau$ Flux*	$\frac{\nu_\mu+\nu_e}{\nu_\tau}$ †	$\nu_\tau+\bar{\nu}_\tau$ Flux*	$\frac{\nu_\mu+\nu_e}{\nu_\tau}$ †
50	1.5×10^3	15	15.6×10^3	17	6.4×10^3	32
100	9.4	32	4.0	48	1.9	19
150	4.4	48	2.5	22	0.51	9.0
200	2.9	38	1.2	11	0.11	4.1
250	2.0	26	0.43	7	0.02	—
300	1.3	14	0.13	—	—	—

* $\nu_\tau+\bar{\nu}_\tau$ from F decay, $(\text{GeV}^{-1}\text{-m}^{-2})/10^{13}$ protons. Averaged over 2 mr radial bin.

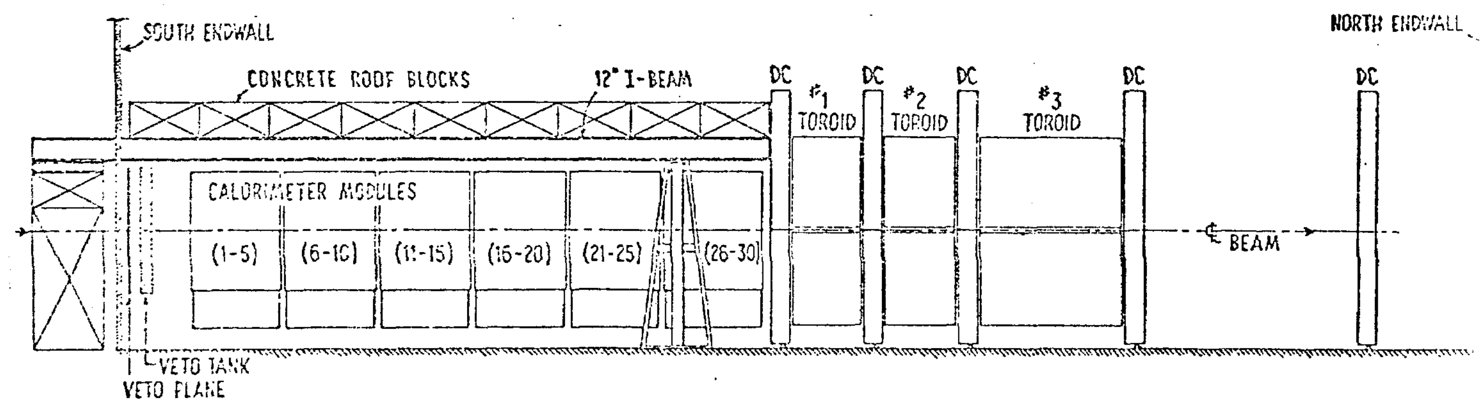
† Includes $\nu+\bar{\nu}$. $\nu_\mu+\nu_e$ from D decay. ν_τ from F-decay

FIGURE CAPTIONS

1. The existing E-613 detector
2. E-613 target and beam dump.
3. Possible configuration of enlarged detector. One of 15 cells is shown.
4. Representative behavior of the ratio of events with electrons to events with muons vs. E_{vis}, the energy deposited in the detector. These curves are scaled from those in Ref. 6. For L fixed, an increase in δm causes the curve to shift to higher energies. Doubling δm, for example, will cause a quadrupling of the energy scale.



PLAN VIEW



ELEVATION VIEW

FIGURE 1

E 613 TARGET AND DUMP MAGNETS

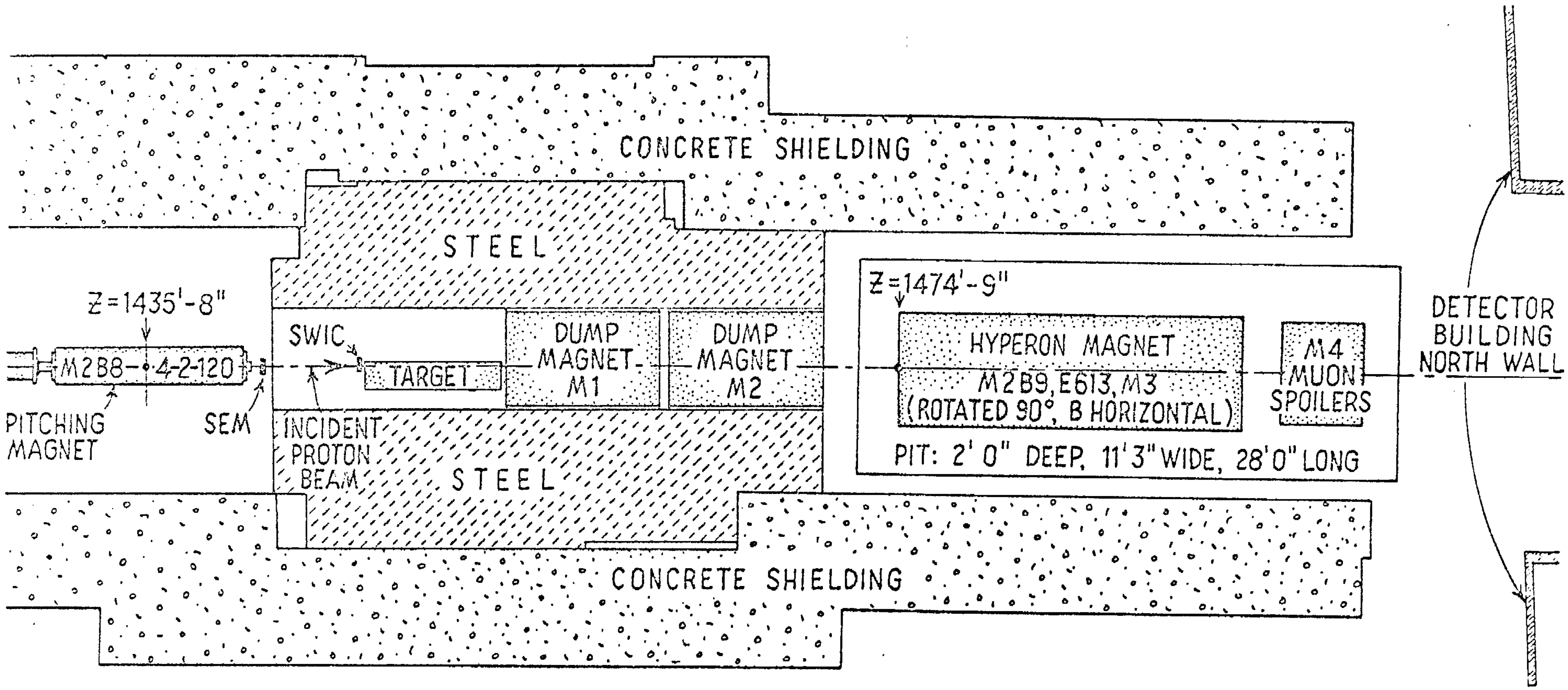


FIGURE 2

ONE OF 15 CELLS OF PROPOSED DETECTOR

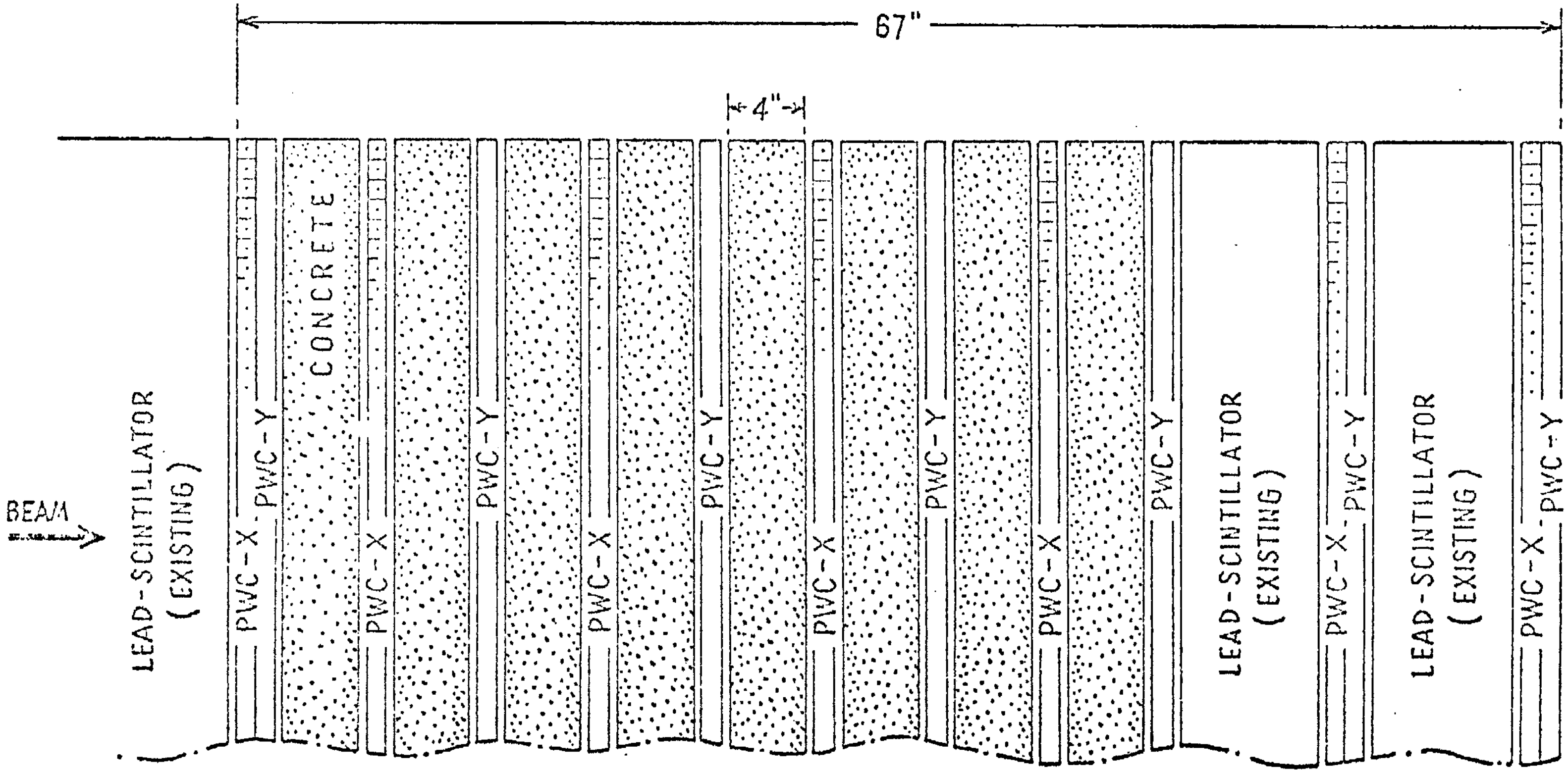


FIGURE 3

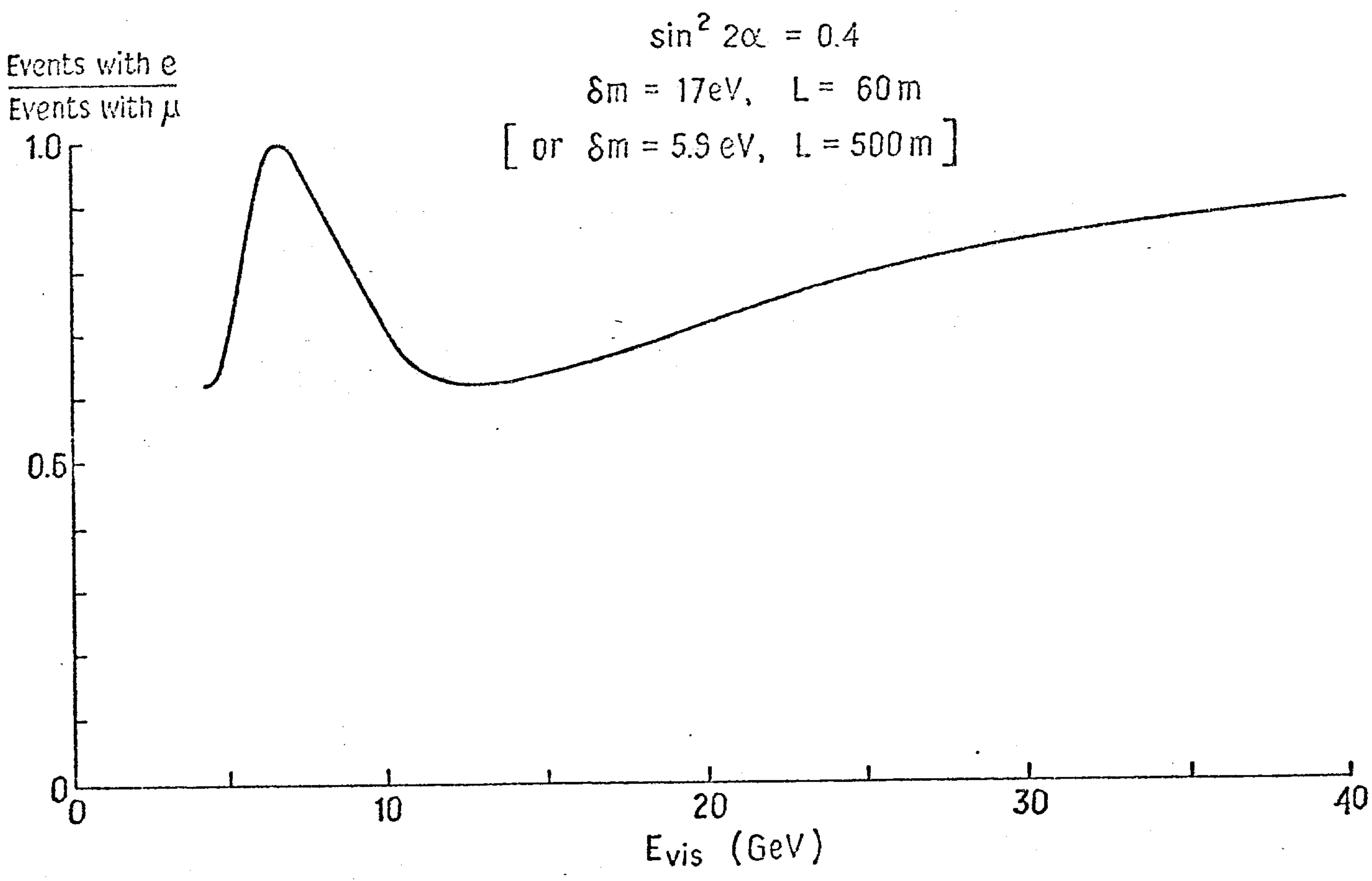

sin² 2α = 0.4
δm = 17eV, L = 60 m
[or δm = 5.9 eV, L = 500 m]
Events with e / Events with μ
1.0
0.5
0
0
10
20
30
40
E_vis (GeV)

FIGURE 4